

Our Ref.: 922-99

U.S. PATENT APPLICATION

Inventor(s): Bryan J. DONOGHUE

Invention: FLOW CONTROL SYSTEM FOR NETWORK DEVICES

***NIXON & VANDERHYE P.C.
ATTORNEYS AT LAW
1100 NORTH GLEBE ROAD
8TH FLOOR
ARLINGTON, VIRGINIA 22201-4714
(703) 816-4000
Facsimile (703) 816-4100***

SPECIFICATION

Attorney Docket:

APPLICATION

FOR

UNITED STATES LETTERS PATENT

Be it known that I, Bryan James Donoghue, a citizen of Great Britain, residing at 32 Ashtree Court, Granville Road, St Albans, Hertfordshire, AL1 5UE, England have invented new and useful improvements in:

FLOW CONTROL SYSTEM FOR NETWORK DEVICES

of which the following is a specification:

FLOW CONTROL SYSTEM FOR NETWORK DEVICES

Field of the Invention

5 This invention relates to flow control in packet-based communication networks and in particular to a flow control system for network devices capable of sending over a duplex link control frames hereinafter called pause frames specifying a selectable pause in the sending of packets by a source connected to the other end of the link. The invention particularly relates to the generation of special pause frames in a manner which is intended
10 to reduce storage requirements in network devices such as switches.

Background to the Invention

15 Packet-based communication systems such as Ethernet systems consist, in terms of hardware, of a multiplicity of links at each end of which two devices send addressed data packets to each other. In general, when a packet is received by a device the addressed data may (if necessary) be read to determine if required the next destination of the packet on its route to the ultimate end station. Typically the packet is temporarily stored. A packet may be stored in memory specifically dedicated to particular ports or may be stored in a
20 common central memory. Typically, whether there is a common central memory or not, each port of a device has FIFO memory associated with it. Whatever may be the arrangements for the temporary storage of packets before they are forwarded from a given device, it is a normal occurrence that a device at one end of a link sends packets or frames to a receiving device at a rate higher than the receiving device can absorb them. The rate
25 of 'absorption' may be influenced by a variety of factors, one being the rate at which the receiving device can forward packets or frames. A second factor is the traffic conditions on links from the receiving device to other devices. A third factor may be the latency, for example inherent delays in processing in the receiving device and so on. It is therefore customary to monitor the occupancy of memory space allotted to a given port or a group
30 of ports and on the production of a signal, indicating according to some selected criterion, usually termed 'watermark', that the memory is sufficiently full, a pause frame is sent by the device to the source of packets for that particular port or group of ports.

It should be understood at this point that a group of ports may be linked together by means of a trunk so as to increase the rate of transmission of packets over a particular link. Further, the choice of a watermark is influenced by latency in the system. For example, it is normally necessary to allow for a round-trip time, i.e. a time including the time for a pause frame to travel to the source device and for packets sent by the source to the receiver. For this reason the watermark usually denotes some proportion of the allotted memory space rather less than the maximum physical capacity of the relevant memory space.

As will be explained later, it is normal practice in current systems, particularly those conforming to IEEE Standard 802.3, to send pause frames which are organised to have a special globally assigned address, a relevant operation code and a pause time. A device conforming to that Standard will on receipt of such a pause frame on a particular link, cease sending packets over the link for the time specified in the pause frame. It is conventional that such a frame overrides the effect of a previous frame, so that the pause (if any) imposed on a source is determined only by the most recently received pause frame. It is also known to organise the sending of pause frames so that when the occupancy of the relevant memory space goes above an upper watermark a pause frame specifying a very long pause time is sent whereas when the occupancy of the memory falls below a lower watermark, a pause frame specifying a zero pause time is sent. The former will be termed herein an XOFF frame whereas the latter will be termed an XON frame, since the latter is interpreted by the source as allowing the sending of packets to recommence over the relevant link.

Owing to the need to accommodate wide variations in traffic conditions, systems sending an XOFF frame at an upper watermark and an XON frame at a lower watermark tend to require excessive memory.

It is therefore the general objection of the present invention to reduce the memory requirements in a system which employs pause frames for controlling the flow of packets over a duplex link.

Summary of the Invention

The invention concerns the sending, when a buffer memory falls below a selected mark, of a periodic sequence of pause frames which impose on the source that is governed by those frames a duty cycle of alternating periods in which sending of packets by the source is allowed and prevented.

The periodic sequence of pause frames can be provided in a variety of ways. One is to send XOFF frames alternating with XON frames at a selected frequency. Another is to send pause frames which specify a pause time which is a fraction of a repetition period of the pause frames.

One benefit of such a scheme is that a device which can operate at a relatively low rate and/or have insufficient memory to be fully compatible with a source that operates at a much higher rate can limit the maximum rate of the source to a fraction of that much higher rate. Alternatively the device needs less memory to cope with a 'worst case' condition in which the source transmits at a high rate and the device empties the memory at a much lower rate.

Further features and objects of the invention will become apparent from the following description by way of example of a particular embodiment of the invention.

Brief Description of the Drawings

Figure 1 illustrates by way of example the relevant parts of a network device which is arranged to receive 'Ethernet' packets and frames over a duplex link;

Figure 2 illustrates packets and frames used by the link;

Figure 3 is a diagram of a processing block used to implement the invention;

Figure 4 is a diagram of a memory space within the device;

Figure 5 is a diagram of periodic pause frame generation applied to a low watermark of a buffer memory;

5 Figure 6 illustrates a preferred process for generating pause frames.

Detailed Description of Preferred Examples

10 Figure 1 illustrates by way of example only part of a network device for use in a packet-based data communication system. An example of such a device is a network switch, bridge, router or adapter which has a multiplicity of ports any one of which may be connected as one end of a communication link over some suitable transmission medium to another device. In normal circumstances some or all of the ports of such a device will be connected to other devices and may both send and receive data packets. For the sake of simplicity it will be presumed that the device shown in Figure 1 is for use as one end of a duplex communication link 10 and a port 11 is connected to that link. Typically, the port 11 contains several 'layers', such as the physical connection sub-layer (PCS), the media access control layer (MAC) and the media independent interface (MII). For an explanation of these terms the reader is directed to the aforementioned Standard.

15 20 The port 11 may be connected to a parser block which reads for example addressed data from packets and controls by means of a pointer block 13 an interface 14 which determines where in a memory 15 a packet received by the port shall be stored. Typically the memory 15 has a memory space allotted to each of the ports. How this is organised is not important to the present invention. Data will be read out from the buffer by means of a read controller 16 driving a read pointer and a read request to the interface 14 which will control the buffer 15. In this example, the occupancy of the memory space available for packets received by port 11 will be determined by the respective read and write pointers obtainable from the RX pointer block 13 and the read controller 16. These pointers are employed by a processing block 17 for the initiation of flow control frames by port 11, the flow control frames being generated in the prescribed format and in a manner known per se by the port 11.

It is emphasised that the architecture shown in Figure 1 is given only by way of example and, apart from the processing block 17, represents by way of example a large number of different types of network device. As will be apparent, the invention is applicable whatever the particular form of the memory provided (as is normal) that the degree of occupancy of the memory can be determined.

For example, Figure 4 illustrates schematically a memory such as memory 15. The memory is coupled to receive packets and also to deliver packets. The memory will have, in general, two predetermined levels or marks. Although the memory may have a multiplicity of such marks, for the sake of simplicity only two will be considered, a 'high watermark' (HWM) and a 'low watermark' (LWM). It is customary to regard the memory space available over and above the high watermark as 'overflow' memory, the memory space which has to be occupied before the low watermark is reached as the 'starvation' memory and the memory capacity between the high watermark and the low watermark as the 'hysteresis' memory.

The high watermark and low watermark merely denote predetermined respective proportions (which may be controllable or defined) of the respective available memory space. Whether the memory is above the HWM or below the LWM may be determined by comparing the difference between the read and write pointers with signals numerically representing the HWM and LWM.

Figure 2 illustrates an ordinary data packet which may be sent or received by the device shown in Figure 1 and a frame 21 which is conventionally prescribed for use as a flow control frame.

The ordinary packets may consist of a start of frame delimiter (SFD), media access control address data usually constituted by a destination address (DA) and a source address (SA), protocol data, which includes for example network address data, followed by message data and cyclic redundancy code (CRC) data. The usage of such packets is well established and will not be described in detail.

Pause frame 21 shown in Figure 2 is a conventionally defined pause frame. In this embodiment of the invention it is intended to conform to the flow control frames described in IEEE Standard 802.3, 1998 Edition, annexes 31a and 31b, pages 1205-1215.

As will be seen, the invention is applicable to analogous forms of pause frames.

The particular form of pause frame 21 described in the Standard includes in place of the media access control data as shown for packet 20, a 'globally assigned' multicast address which is specified (and reserved) for use in MAC pause frames to inhibit transmission of data frames from a data transmission entity in a full duplex mode. The pause frame includes a special operation code, known as the 'pause' op-code and a request operand which indicates the length of time for which inhibition of data frame transmission from the far end of the link is desired. The request operand specifies a 16-bit number (n) which prescribes a delay of $k \cdot n$ bit times where $k = 512$, and n can vary from zero to $2^{16} - 1$.

As is described in the Standard, a data source which receives a pause frame of this nature is required to cease the sending of data packets for the pause time. How it does this is not important to the present invention and is in any event at the choice of the user provided that the operation conforms to the Standard. Obviously, similar considerations must apply for other forms of pause frames.

Typically however a source will include a timer which is set on receiving a pause frame and the source may recommence transmission of packets when the timer value reaches zero (i.e. times out). If the received pause frame indicates a zero time, the timer is immediately set to zero. If a new pause frame is received the timer is reset to the new pause time.

Accordingly, it is known practice to define two types of pause frames, of which one XON specifies zero time, and thus defines a transmission ON state. The other ('XOFF') may specify a pause time which is very long and therefore can effectively define an 'OFF' state. In the example given the maximum pause time corresponds to approximately 32

megabits. An XOFF frame may define this maximum time but need not. It is possible (though not desirable) for the XON pause time to be very small rather than zero.

Figure 3 illustrates schematically a processing block 17. It will receive on lines 30 and 31 the read and write pointers, to provide a measure of the state of fullness of the respective memory space, signals representing the HWM and LWM on lines 32 and 33 and will produce a flow control initiating signal on a line 34. It is a state machine which implements the process shown in Figure 6. As will be apparent, in the preferred example the frequency of the pause frame sequence is fixed and so are the pause times, but for completeness means for setting the interval between the start of the XON frame and the start of the next XOFF frame is shown at 35 and means for setting the interval between the start of the XOFF frame and the start of the XON frame is shown at 36. These may be controlled by the network management process.

Known forms of processing blocks, such as shown for example in our earlier patent application number 9905482.7 filed 11 March 1999, include inputs defining a pause time (which may be dependent on the state of fullness of the memory) and other inputs which are not particularly relevant to the present invention.

Referring to Figure 4, it is customary to send a pause frame with a very long pause period defined in it (an XOFF frame) when the occupancy of the memory space exceeds the high watermark and to send a pause frame defining substantially zero pause period (an XON frame) when the occupancy of the memory has fallen below the low watermark. It is preferable to separate the high watermark from the low watermark to provide what is termed the 'hysteresis' memory.

An algorithm in which an XOFF frame is sent when the high watermark is exceeded and an XON frame sent when the low watermark is reached will accomplish flow control but in practice requires a large amount of 'overflow' memory in the buffer above the capacity prescribed by the high watermark. The overflow memory required is influenced by the peak data rate and the time required between the sending of an XOFF frame by the receiving device and the time when data packets cease to arrive at the device. Typically,

for a link operating with a peak rate of 10 gigabits per second, and being longer than for example 250 metres, the time taken is dominated by the round trip propagation delay of the link. For a 10 gigabit per second link of length 40 kilometres, at least 4 megabits of overflow memory would be required. This is a large memory for incorporation in an ASIC and any reduction would lead to at least a cost advantage, bearing in mind that an ASIC may be required for each of a large multiplicity of ports on a device.

A modified algorithm for sending pause packets is shown in Figure 6 and may be understood in conjunction with Figure 5.

Figure 5 shows in its upper portion a graphical line 50 representing the occupancy of the memory space against time. The middle portion illustrates the pause status of the receiver, wherein a transition between XON and XOFF represents the sending of an XOFF control frame and the reverse transition represents the sending of an XON control frame. The lowermost portion of Figure 5 represents the transmit status of the source, i.e. the effect on it of the pause control frames. This status corresponds to the pause status but is delayed relative to it by the time for propagation of the frames from receiver to source. For simplicity it is assumed that the source will whenever permitted transmit at its maximum data rate (e.g. 10 Gigabits per second) and that the receiver continually empties its buffer memory at its maximum data rate (e.g. 4 Gigabits per second) and that it is desirable to limit the data rate of the source to an average of about that of the receiver.

The processing unit repeatedly executes the process shown in Figure 6 as often as suitable, for example at a rate equivalent to the rate at which packets are received.

The process is presumed (without loss of generality) to commence at a time when L (representing the occupancy of the memory) approaches the HWM. The duty cycle is commenced at this time.

When the occupancy of the memory space exceeds the high watermark, as shown by curve 50 at time t1, the device will send only XOFF frames on link 10 to the remote source device. After a time delay due to the propagation time for frames and packets on the link,

the sending of packets by the source must cease (time t2). After the source/receiver propagation delay the reception of packets by the receiver ceases (at time t3). When the input buffer empties below the low watermark as shown by curve 50 at time t4, the device will send a periodic alternating sequence of XON and XOFF control frames. The time period between the pause packets and the intervals between the sending of an XOFF control frame and an XON frame and vice versa may be different and may be set into the processing block by means of control inputs 35 and 36. These may be regarded as ON and OFF times (but should not be confused with the pause times defined by the frames).

At time t5 the first XON frame arrives at the source so that the source can transmit intermittently at the reduced data rate. By selecting the ON and OFF times the source's data rate can be reduced to any desired fraction of the maximum rate of the source.

At time t6 packets from the source again arrive at the receiver and curve 50 rises at the net rate (i.e. the incoming data rate less the rate at which packets are removed from the memory). At time t7 the contents are above the LWM but in this embodiment the duty cycle continues to time t8, which corresponds to time t1. At this point the alternating sequence ends and the receiver sends only XOFF frames as before. At time t9 the source receives only XOFF frames, as at time t2.

In this manner the remote source is effectively controlled so that it cannot send packets more quickly than D^* (maximum data rate) where D is the duty cycle (i.e. the ON time divided by the sum of the ON and OFF times). Under these circumstances the overflow memory required by the receiver can be reduced to the similar proportion of the overflow memory required for ordinary flow control. Thus for example a 10 gigabit per second link which is 40 km long and subject to a 40% duty cycle will now only require 1.6 megabits of overflow memory.

Various modifications are possible. For example, although the alternating sequence of XON and XOFF flow control frames continues when the content of the memory exceeds the mark LWM (at time t6 shown) it could be stopped when the memory exceeded the low watermark. Further, the sequence may be constituted entirely by pause frames which

prescribe a pause time which is less than their repetition period, so that the source reverts to its ON state because the pause timer times out substantially before the next pause frame is received. For example pause frames defining a pause time of $1\mu\text{s}$ may be sent every $2\mu\text{s}$.

5

Further, although the preferred embodiments do not require any measurement of the net data rate of the memory (for example by measuring change of the difference between read and write pointers in unit time) such a measurement may be made and employed to control the duty cycle.

10

11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000
1001
1002
1003
1004
1005
1006
1007
1008
1009
1010
1011
1012
1013
1014
1015
1016
1017
1018
1019
1020
1021
1022
1023
1024
1025
1026
1027
1028
1029
1030
1031
1032
1033
1034
1035
1036
1037
1038
1039
1040
1041
1042
1043
1044
1045
1046
1047
1048
1049
1050
1051
1052
1053
1054
1055
1056
1057
1058
1059
1060
1061
1062
1063
1064
1065
1066
1067
1068
1069
1070
1071
1072
1073
1074
1075
1076
1077
1078
1079
1080
1081
1082
1083
1084
1085
1086
1087
1088
1089
1090
1091
1092
1093
1094
1095
1096
1097
1098
1099
1100
1101
1102
1103
1104
1105
1106
1107
1108
1109
1110
1111
1112
1113
1114
1115
1116
1117
1118
1119
1120
1121
1122
1123
1124
1125
1126
1127
1128
1129
1130
1131
1132
1133
1134
1135
1136
1137
1138
1139
1140
1141
1142
1143
1144
1145
1146
1147
1148
1149
1150
1151
1152
1153
1154
1155
1156
1157
1158
1159
1160
1161
1162
1163
1164
1165
1166
1167
1168
1169
1170
1171
1172
1173
1174
1175
1176
1177
1178
1179
1180
1181
1182
1183
1184
1185
1186
1187
1188
1189
1190
1191
1192
1193
1194
1195
1196
1197
1198
1199
1200
1201
1202
1203
1204
1205
1206
1207
1208
1209
1210
1211
1212
1213
1214
1215
1216
1217
1218
1219
1220
1221
1222
1223
1224
1225
1226
1227
1228
1229
1230
1231
1232
1233
1234
1235
1236
1237
1238
1239
1240
1241
1242
1243
1244
1245
1246
1247
1248
1249
1250
1251
1252
1253
1254
1255
1256
1257
1258
1259
1260
1261
1262
1263
1264
1265
1266
1267
1268
1269
1270
1271
1272
1273
1274
1275
1276
1277
1278
1279
1280
1281
1282
1283
1284
1285
1286
1287
1288
1289
1290
1291
1292
1293
1294
1295
1296
1297
1298
1299
1300
1301
1302
1303
1304
1305
1306
1307
1308
1309
1310
1311
1312
1313
1314
1315
1316
1317
1318
1319
1320
1321
1322
1323
1324
1325
1326
1327
1328
1329
1330
1331
1332
1333
1334
1335
1336
1337
1338
1339
1340
1341
1342
1343
1344
1345
1346
1347
1348
1349
1350
1351
1352
1353
1354
1355
1356
1357
1358
1359
1360
1361
1362
1363
1364
1365
1366
1367
1368
1369
1370
1371
1372
1373
1374
1375
1376
1377
1378
1379
1380
1381
1382
1383
1384
1385
1386
1387
1388
1389
1390
1391
1392
1393
1394
1395
1396
1397
1398
1399
1400
1401
1402
1403
1404
1405
1406
1407
1408
1409
1410
1411
1412
1413
1414
1415
1416
1417
1418
1419
1420
1421
1422
1423
1424
1425
1426
1427
1428
1429
1430
1431
1432
1433
1434
1435
1436
1437
1438
1439
1440
1441
1442
1443
1444
1445
1446
1447
1448
1449
1450
1451
1452
1453
1454
1455
1456
1457
1458
1459
1460
1461
1462
1463
1464
1465
1466
1467
1468
1469
1470
1471
1472
1473
1474
1475
1476
1477
1478
1479
1480
1481
1482
1483
1484
1485
1486
1487
1488
1489
1490
1491
1492
1493
1494
1495
1496
1497
1498
1499
1500
1501
1502
1503
1504
1505
1506
1507
1508
1509
1510
1511
1512
1513
1514
1515
1516
1517
1518
1519
1520
1521
1522
1523
1524
1525
1526
1527
1528
1529
1530
1531
1532
1533
1534
1535
1536
1537
1538
1539
1540
1541
1542
1543
1544
1545
1546
1547
1548
1549
1550
1551
1552
1553
1554
1555
1556
1557
1558
1559
1560
1561
1562
1563
1564
1565
1566
1567
1568
1569
1570
1571
1572
1573
1574
1575
1576
1577
1578
1579
1580
1581
1582
1583
1584
1585
1586
1587
1588
1589
1590
1591
1592
1593
1594
1595
1596
1597
1598
1599
1600
1601
1602
1603
1604
1605
1606
1607
1608
1609
1610
1611
1612
1613
1614
1615
1616
1617
1618
1619
1620
1621
1622
1623
1624
1625
1626
1627
1628
1629
1630
1631
1632
1633
1634
1635
1636
1637
1638
1639
1640
1641
1642
1643
1644
1645
1646
1647
1648
1649
1650
1651
1652
1653
1654
1655
1656
1657
1658
1659
1660
1661
1662
1663
1664
1665
1666
1667
1668
1669
1670
1671
1672
1673
1674
1675
1676
1677
1678
1679
1680
1681
1682
1683
1684
1685
1686
1687
1688
1689
1690
1691
1692
1693
1694
1695
1696
1697
1698
1699
1700
1701
1702
1703
1704
1705
1706
1707
1708
1709
1710
1711
1712
1713
1714
1715
1716
1717
1718
1719
1720
1721
1722
1723
1724
1725
1726
1727
1728
1729
1730
1731
1732
1733
1734
1735
1736
1737
1738
1739
1740
1741
1742
1743
1744
1745
1746
1747
1748
1749
1750
1751
1752
1753
1754
1755
1756
1757
1758
1759
1760
1761
1762
1763
1764
1765
1766
1767
1768
1769
1770
1771
1772
1773
1774
1775
1776
1777
1778
1779
1780
1781
1782
1783
1784
1785
1786
1787
1788
1789
1790
1791
1792
1793
1794
1795
1796
1797
1798
1799
1800
1801
1802
1803
1804
1805
1806
1807
1808
1809
1810
1811
1812
1813
1814
1815
1816
1817
1818
1819
1820
1821
1822
1823
1824
1825
1826
1827
1828
1829
1830
1831
1832
1833
1834
1835
1836
1837
1838
1839
1840
1841
1842
1843
1844
1845
1846
1847
1848
1849
1850
1851
1852
1853
1854
1855
1856
1857
1858
1859
1860
1861
1862
1863
1864
1865
1866
1867
1868
1869
1870
1871
1872
1873
1874
1875
1876
1877
1878
1879
1880
1881
1882
1883
1884
1885
1886
1887
1888
1889
1890
1891
1892
1893
1894
1895
1896
1897
1898
1899
1900
1901
1902
1903
1904
1905
1906
1907
1908
1909
1910
1911
1912
1913
1914
1915
1916
1917
1918
1919
1920
1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070
2071
2072
2073
2074
2075
2076
2077
2078
2079
2080
2081
2082
2083
2084
2085
2086
2087
2088
2089
2090
2091
2092
2093
2094
2095
2096
2097
2098
2099
2100
2101
2102
2103
2104
2105
2106
2107
2108
2109
2110
2111
2112
2113
2114
2115
2116
2117
2118
2119
2120
2121
2122
2123
2124
2125
2126
2127
2128
2129
2130
2131
2132
2133
2134
2135
2136
2137
2138
2139
2140
2141
2142
2143
2144
2145
2146
2147
2148
2149
2150
2151
2152
2153
2154
2155
2156
2157
2158
2159
2160
2161
2162
2163
2164
2165
2166
2167
2168
2169
2170
2171
2172
2173
2174
2175
2176
2177
2178
2179
2180
2181
2182
2183
2184
2185
2186
2187
2188
2189
2190
2191
2192
2193
2194
2195
2196
2197
2198
2199
2200
2201